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QUALITY PERFORMANCE OF AL-SI-MG-CU ALLOYS

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ABSTRACT

This article was undertaken to investigate the Quality index charts with the purpose of setting the limits of the tensile properties, as well as to compare the mechanical behavior of cast Al-Si-Mg-Cu alloys, to delineate the effect of the solution treatment applied. Tensile properties upon artificial aging in the temperature range of 155–350°C for times ranging from 2 to 100 hours were also investigated. The results showed that the use of quality index charts is a satisfactory method for presenting tensile test results, for assessing the effect of solution and aging treatment conditions subjected to the modified grain-refined alloys. It is also observed that the quality index, Q, is more sensitive to variations in the tensile ductility than to tensile strength.

KEYWORDS: Temperature Range of 155–350°C, Intersection of the Flow Curves at a Plastic Strain of 0.2%, Respectively

INTRODUCTION

Aluminum-silicon-copper-magnesium alloys such as the 354 alloys show a greater response to heat treatment as a result of the presence of both Mg and Cu. These alloy types display excellent strength and hardness values although at some sacrifice of ductility and corrosion resistance. These alloys are used for a wide range of applications, including engine cooling fans, crankcases, high speed rotating parts, structural aerospace components, air compressor pistons, fuel pumps, compressor cases, timing gears, rocker arms, machine parts, and so forth [1,2].

Any improvement in mechanical properties is commonly evaluated through the tensile properties. Almost all of the steps in the processing of aluminum, from establishing a composition to heat-treatment, produce a variation in mechanical properties. The fact that tensile properties depend on several variables may go far to explain the confusion existing in connection with the properties of cast aluminum alloys.

Quality Index is a pivotal concept originally developed by Drouzy, Jacob and Richard [3] who introduced an empirical parameter Q, or quality index, to characterize the mechanical performance of Al-7%Si-Mg casting alloys. The quality indexis relatedto the tensile strength, UTS, and the plastic strain of the material to fracture, s_f, as represented by equation 1.

$$\mathbf{Q = UTS + d \log (s_f)} \tag{1}$$

While the constant yield strength lines are represented by equation 2

$$\mathbf{YS = a\,UTS - b \log (\mathit{s_f}) - c} \tag{2}$$

Although the concept was developed specifically for alloys 356 and 357, it has occasionally been applied to other alloy systems as well [4-8]. A model developed by Cáceres [6] shows that the *iso-Q* lines represent contours of constant

relative ductility, the latter thus providing a simple physical rationale for the Q parameter. The Cáceres model assumes that the material can be described with a constitutive equation of the form:

$$\sigma = K\varepsilon^n \tag{3}$$

where σ is the true flow stress, K is the strength coefficient, n is the strain-hardening exponent, and ε is the true plastic strain. The parameter n relates to the strain-hardening rate, $d\sigma/d\varepsilon$, through the equation [9]

$$n = \varepsilon/\sigma \; d\sigma/d\varepsilon \tag{4}$$

If the elastic component of the strain is disregarded and assuming that true and nominal strain are equivalent (*i.e.* $s \approx \varepsilon$), which is a reasonable assumption for casting alloys due to their limited ductility, then the nominal stress-strain curve can be approximated by

$$P = K[\ln(1+s)]^n \, e^{-\ln(1+s)} \approx K s^n e^{-s} \tag{5}$$

The iso-quality lines can also be generated using Equation 5 by introducing the relative ductility parameter, q, defined as the ratio between the strain-hardening exponent of the material and the elongation to fracture, s_f,

$$q = s_f / n \tag{6}$$

where $q = 1$ with the samples reach necking (*i.e.* the most ductile samples), while $q < 1$ identifies progressively less ductile samples. Solving Equation 6 for n and substituting in Equation 5, gives

$$P = K s^{s/q} \, e^{-s} \tag{7}$$

Differentiation of Equation 7 with respect to strain, s, taking into account parameter d in Equation 1, to k and q as follows:

$$d = - dP/ds = - (s/mq) \, P \, [1 + \ln(s) - q\,]$$

$$= - (s/mq) \, K \, s^{s/q} \, e^{-s} \, [1 + \ln(s) - q] \tag{8}$$

where $m = 0.434$. The negative sign has been added to keep this formulation consistent with Equation 1.

An approximation of Equation 8 could be Equation 9 which may arise as a result of combining Equations 1 and 7, considering that Equation 7 is a valid equation for whatever the value of q might be. Equation 9 makes it possible to calculate the quality index from the tensile test results based solely on the knowledge of the value of K.

$$Q = UTS + 0.4 \, K \log(s_f) \tag{9}$$

Quality Index charts are thus a viable option for presenting results obtained from tension tests considering that the UTS, YS (intersection of the flow curves at a plastic strain of 0.2%), and plastic strain % may be read in one and the same plot. Additionally, the relative ductility, as well as the quality index which corresponds to these same properties. Using the model developed by Cáceres [7,10], it is possible to design a quality index chart for any alloy, comparing different alloys in one single plot in such a way that it becomes possible to define the effects related to changes occurring in chemical composition, microstructure, and heat treatments within the mechanical properties under study.

Quality index charts are used in the present study with the purpose of setting the limits of the tensile properties, as well as to compare the mechanical behavior of the of cast Al-Si-Mg-Cu alloy studied, to delineate the effects of the solution and aging treatments applied.

EXPERIMENTAL PROCEDURES

The as-received 354 alloy was received in the form of 12.5 Kg ingots, the chemical composition of which is given in Table 1. The metal temperature was maintained at 780°C**,** while the melt was degassed using pure, dry argon injected into the melt for 20 min by means of a rotating graphite impeller at 200 rpm. Grain refining and modification of the melt were carried out using Al-5% Ti-1% B and Al-10% Sr master alloys, respectively, to obtain levels of 0.25% Ti and 200 ppm Sr in the melt. The modified grain-refined alloy is coded Alloy A.

The test bars were solutionheat-treated at 495^{o}C for 8 hours, then quenched in warm water at 60ºC, followed by artificial aging at different time and temperatures asshown in Table 2. In addition, three sets of bars are aged at 190 ^{o}C for 200, 600**,** and 1000 hours. The solution and aging heat treatments were carried out in a forced-air Blue M Electric Furnace equipped with a programmable temperature controller (±2 ^{o}C). After aging, the test bars are allowed to cool naturally at room temperature (25°C).

RESULTS AND DISCUSSIONS

Figure 1 reveals the microstructure of modified gain-refined of 354 alloy in as-cast and solution-treated conditions.A complete modification of the silicon particles in the microstructure of alloy A in the as-cast condition may be observed in Figure 1(a). It may be observed from Figures1(a, b) solution heat treatment has the effect of changing the morphology of the silicon particles from faceted to globular; together with this change, which occurs as a consequence of solution heat treatment,there may also be observed a reduction in the number of silicon particles and a reduction in the density of the silicon phase from 14 to 10% as a result of the diffusion of silicon into the aluminum matrix.

Table 3 presents the UTS, YS and %Elongation values for the as-cast (AC)and solution heat-treated (SHT) conditions.In spite of the relatively low solution heat treatment temperature of 495^{o}C used in this work, increased strength after the treatment is normally to be observed in similar 354 alloys which use a solution heat treatment temperature of 525^{o}C over a 2-3 hour period, in conjunction with analogous aging treatments [11,12]. The strength values, particularly the UTS, increased by as much as 30 pct between the as-cast (AC) and the solution heat-treated (SHT) conditions. The changes in the morphology of the silicon particles during solution heat treatment may be observed principally in the increase of the ductility values rather than in that of the strength values; with regard to both the as-cast and solution-treated conditions, the difference in yield strength is no more than 5 pct whereas it is over 290 pct for elongation. The increase in ductility may be explained as follows: the silicon particles act as stress concentrators since they are harder than the matrix; serving as stress concentration sites, such particles tend to promote crack propagation during load application thereby principally decreasing the ductility of the alloy.

The effects of solution heat treatment on the spheroidization of such particles tends to decrease the stress concentration as the silicon particles become increasingly more rounded with the progress of solution treatment at the specified solution temperature.Figures 2 through 4 show the tensile properties of modified grain-refined 354 alloy for the several aging times and temperatures applied during the heat treatment. Through solution heat treatment and artificial aging, the strength of alloy was increased by ~64 pct over its as-cast strength. It may be observed from Figure 2, the maximum value for UTS of ~386 MPa may be obtained with three different sets of aging conditions, *i.e.* 155°C/100hrs, 170°C/10hrs, and 190°C/2hrs. The greatest mechanical stability for the aging treatments was to be observed at 155°C and the second greatest at 170^{o}C.

Considering the yield strength value in the solution heat-treated condition, in conjunction with the artificial aging conditions used, it was possible to increase the yield strength value by more than 100 pct. The maximum yield strength was reached after 100 hours at the aging temperature of 155^{o}C, after 48 hours at 170^{o}C, and after 2 hours at 190^{o}C.

When considering the whole range of aging treatments applied in this work, the greatest decrease in tensile strength may be observed at 240^{o}C, going from 312 MPa at 2 hours to 240 MPa at 100 hours. In the same way, a significant decrease in strength going from 382 MPa at 2 hours to 314 MPa at 100 hours is also to be observed at 190^{o}C. Even though a significant decrease in the alloy strength is not in evidence from 2 to 100 hours at 300^{o}C and 350^{o}C, nonetheless, the greatest mechanical deterioration will be observed after less than 2 hours of aging treatment. This previous assumption is based on a consideration of the tensile properties of the material upon solution heat treatment, namely, UTS = 305 MPa and YS = 161 MPa, implying that the over-aged samples tended to lose between 15% and 40% of their original strength within the first 2 hours of being subjected to aging at temperatures of 300^{o}C and 350^{o}C.

The general behavior of Alloy with regard to ductility displays a decrease from 155°C to 190°C, as shown in Figure 4. A lower ductility value is observed for the condition involving 190°C for 12 hours in the experimental alloy test samples. Increased ductility may be observed above 190°C as the aging temperature increases. The greatest ductility values may be observed for aging at 350°C, although none of the aging conditions reaches the higher ductility values shown in the solution heat-treated condition. This observation may be considered evidence that the mechanical behaviour displayed by alloy is common to that of the Al-Si-Cu-Mg alloys whose strength is obtained at the expense of ductility [13, 14]

After 2 hours of aging at 190°C, the tensile properties attain the highest strength values while exhibiting the lowest ductility of all the aging conditions applied. The yield strength behavior appears to be the most stable at 190°C aging temperature, showing a variation of 50 MPa in yield strength values for aging times between 2 and 100 hours. These observations were taken into account for the selection of this specific temperature for experiments designed to investigate how the mechanical properties may be affected by long exposure times.

The Quality index charts presented here are explained for a single specific condition with regard to Alloy, namely the solution-heat-treated condition. For explicative details regarding the construction of the Quality index charts, the values corresponding to the five tests for the solution heat-treated condition and their averages as well as the standard deviations are presented in Table 4.Figure 5 shows the engineering stress-strain flow curve for the solution heat-treated condition - Test 3 relating to alloy. Conversion from engineering stress-strain curve to true stress-strain curve may be obtained from the relationship between the formulae 1 and 2 [15].

$$\boldsymbol{\sigma = (P/A_0)\,(e_{\mathrm{plastic}} + 1) = \mathrm{s}\,(e_{\mathrm{plastic}} + 1)} \tag{10}$$

$$\boldsymbol{\varepsilon_{\mathrm{plastic}} = ln\,(e_{\mathrm{plastic}} + 1)} \tag{11}$$

where $\boldsymbol{P}$ is the load applied over the original cross-sectional area, $\boldsymbol{A}$, of the tensile sample**,** **σ** is the true-stress, **ε** is the true-strain, $\boldsymbol{s}$ is the engineering stress, and $\boldsymbol{e}$ is the engineering strain.

Figure 6 shows a comparison of two curves, a black curve which is the flow curve corresponding to the example shown in and a red curve which follows the values obtained using Holloman's equation $\boldsymbol{\sigma = K\varepsilon^n}$ and using the values of $\boldsymbol{n}$ = 0.193 and $\boldsymbol{K}$ = 528 obtained from the Test 3 data. The same procedure was repeated for the different heat treatment conditions applied to alloys studied.

The Cáceres method which is used here for constructing the quality index charts involves the use of a single value of the strength coefficient (***K***) for all the conditions appearing in the charts. The value K = 500 MPa was taken as the average K value for constructing the quality index (QI), where Equation 10 was used to obtain the Quality Index (*Q*).

The average value of the strength coefficient (***K***) is K = 502 as used in the Quality Index charts for all the conditions applied in relation to the seven alloys studied, that is to say, 161 conditions in total. The value of K was rounded to500 and used to represent the average value for all conditions when the quality index was calculated.

Returning to the example Test 3, the error percentage is calculated as 1.32% which appears to be a satisfactory approximation for this specific condition. This type of comparison provides a means for quantifying the percentage of error persisting in the model for the quality index charts as used in this research. Thus, using K = 500 MPa to construct the Quality Index charts for the alloys used in this work may be deemed a reasonable proposition.

Figure 7presents Quality Index chart showing the lowest and highest mechanical quality occurring in the as-cast (AC) and solution heat-treated (SHT) conditions, respectively. Between each one of these conditions there exists a difference of nearly 70 MPa in UTS, while for both cases the YS is virtually similar. In order to analyze mechanical quality by means of the Quality Index charts**,** 20 conditions by alloy were selected from among the whole conditions used**;** such conditions are the as-cast and the solution heat treated conditions plus 18 aging conditions by alloy; the 18 conditions are 2, 10**,** and 100 hours for every aging temperature of 155°C, 170°C, 190°C, 240°C, 300°C**,** and 350°C. The reason for taking only 20 conditions out of a total of 80**,** by alloy**,** was principally to avoid an overcrowded Quality Index chart in which it would not be possible either to discern or to show the general mechanical behaviour of the total of experiments carried out for this research.

The criterion applied for using these 20 conditions (including the as-cast and SHT conditions) was to take into consideration the extreme values, particularly those regarding the pct elongation and yield strength values. As was observed in Figures 3 to 5, these 20 values show the maximum and minimum mechanical properties out of the whole set of experiments carried out for the purposes of this research.

The plastic strain and the quality index (*Q*) both display a significant increase upon solution heat treatment, in spite of the fact that the relative ductility (*q*) attains a value of 0.31 implying that Alloy A in its solution-treated condition has reached 31% of its maximum quality index value (*Q*). The usefulness of *q* as a complementary parameter expresses how far a particular sample is from its maximum possible ductility q = 1; even though, a *q*-value <1 indicates that it would be possible to manipulate the microstructure, for instance, by reducing the SDAS, or the porosity, or the Fe-level to increase the ductility and hence, ultimately, the quality index, Q. When the ductility increases sharply from the as-cast to the solution heat treated condition, such changes can be related to the spheroidization of silicon particles and to the uniformity of the microstructure in the solution heat-treated condition, as shown in Figures 1(a) and 1(b).

The greater part of the behavior of Alloy A under different heat-treatment conditions illustrated in Figures 2, 3, and 4 is displayed through the quality index chart provided in Figure 7. Furthermore, by taking into consideration all the aging temperatures, it becomes possible to detect mechanical behavior which is similar to that displayed by alloy 319 as evidenced by the curvilinear aspect of the quality index as it emerges throughout the aging process of the material [13].The contour curve observed in the quality index chart can be related to changes in the yield strain and strain-hardening which are principally due to the effects of aging time and temperature on the precipitation-hardening of copper phase particles.

A contrary relationship may be observed between *n* and *YS* in view of the fact that artificial aging increases both temperature and time. The form of these two plots in Figure 9 is related to the contour curve observed in the Quality Index

chart shown in Figure 8; the YS reaches a maximum and then decreases after the 190°C/2hr condition when the strain-hardening coefficient reaches a minimum followed by an increase in value as either the temperature or the time, or both, are increased. Below the 190°C/2hr condition, GP zones and θ' precipitates develop such that they are coherent with the matrix [13], YS is thus increased because of the strain fields associated with these precipitates, which are sheared by the dislocations and subsequently lead to a low strain-hardening rate.

The experiments involving long exposure times consisted of three conditions, namely, 200, 600, and 1000 hours at 190°C. The solution heat-treated condition including 2, 10, and 100 hours at 190°C were added to the plot in order to amplify the perspective of the effects of time exposure during aging at such temperature. The same contour curve observed in Figure 8 may be observed in Figure 8 which shows the Quality Index chart pertaining to the 190°C aging temperature for long exposure times.

As may be observed from Figure 8, beyond 2 hours, aging time appears to have little or no effect on the mechanical quality of the alloy at 100, 200, 600 and 1000 hours, as the quality index value remains situated between 315 and 350 MPa, despite the increase in ductility from 1.15% to 2.69% when exposure time is increased from 100 to 1000 hours.

The yield strength is most affected since it decreases by 60 pct, whereas the UTS decreases by only 22 pct over the aging times studied. The tensile properties after a long exposure time at 190°C are comparable to those observed after artificial aging at 240°C from 10 to 100 hours of exposure. The results discussed here are integral evidence that the mechanical properties obtained for Alloy A depend strongly on its thermal history.

CONCLUSIONS

- The conditions/tensile properties which characterize the mechanical behaviour of the 354 alloy studied are located on the quality index charts, where the Quality index attains minimum and maximum values, 259 MPa and 459 MPa, in the as-cast and solution heat-treated conditions, respectively; the yield strength shows a maximum of 345 MPa and a minimum of 80 MPa within the whole series of aging treatments applied.
- It is also consistent that Q is more sensitive to variations in the tensile ductility than to tensile strength.
- The contour curve observed in the quality index chart can be related to changes in the yield strain and strain-hardening which are principally due to the effects of aging time and temperature on the precipitation-hardening of copper phase particles.

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APPENDICES

List of Tables

Table 1: Chemical Composition of the as - Received 354 Alloy

Element (Wt %)					
Si	**Fe**	**Cu**	**Mn**	**Mg**	**Al**
9.1	0.12	1.8	0.0085	0.6	87.6

Table 2: Artificial Aging Conditions Used for Room Temperature Tension Tests

Temperature(°C)	Aging Time (H) and Aging Condition Codes												
	2	**4**	**6**	**8**	**10**	**12**	**16**	**20**	**24**	**36**	**48**	**72**	**100**
155	1	2	3	4	5	6	7	8	9	10	11	12	13
170	14	15	16	17	18	19	20	21	22	23	24	25	26
190	27	28	29	30	31	32	33	34	35	36	37	38	39
240	40	41	42	43	44	45	46	47	48	49	50	51	52
300	53	54	55	56	57	58	59	60	61	62	63	64	65
350	66	67	68	69	70	71	72	73	74	75	76	77	78

Table 3: Mechanical Values, UTS, YS and %Elongation for Modified Grain-Refined 354 Alloy

Condition	UTS	YS	%El
AC	235	154	1.63
SHT	305	161	6.36

Table 4: Tensile Test Results for Solution Heat-Treated Alloy

Test	UTS(MPa)	YS(MPa)	El. (%)
1	307.2	163	6.4
2	302.67	160.99	6.08
3	306.94	162.54	6.39
4	299.66	158.04	6.49
5	308.66	164.42	6.47
Average	**305.03**	**161.8**	**6.37**
Std. Dev.	**3.74**	**2.43**	**0.167**

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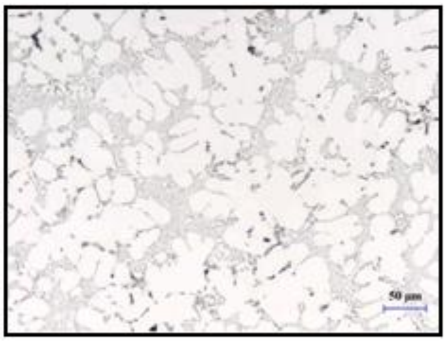
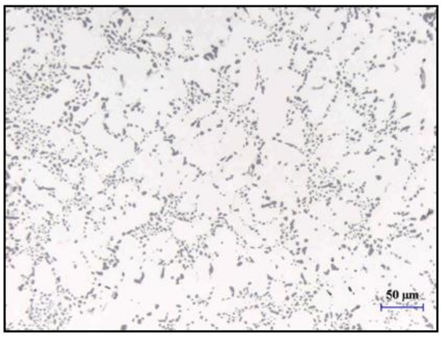


(a)



(b)

Figure 1: Micrographs of a Tensile Test Specimen of Modified Grain-Refined 354 Alloy, Showing the Microstructure in (A) The as-Cast and (B) Solution Heat Treatment Conditions

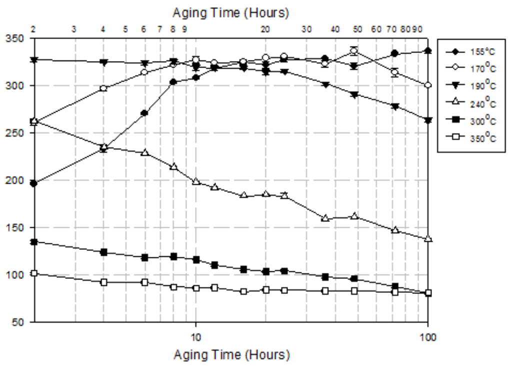


Figure 2: Ultimate Tensile Strength as a Function of Aging Conditions

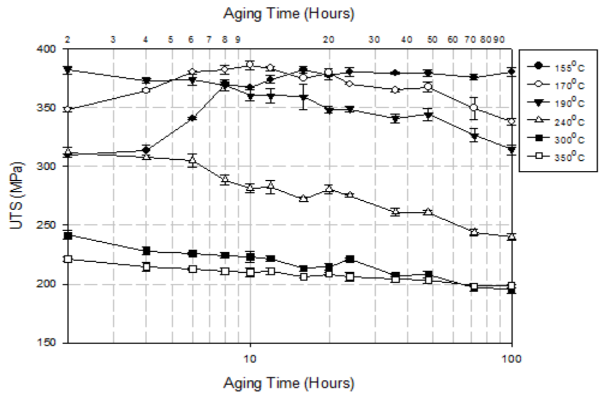


Figure 3: Yield Strength as a Function of Aging Conditions

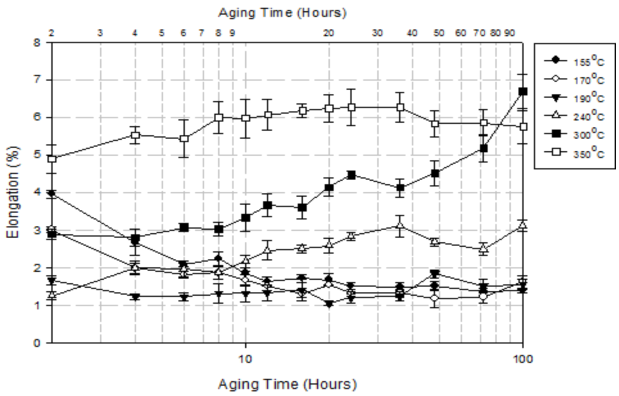


Figure 4: Strain at Fracture as a Function of Aging Conditions

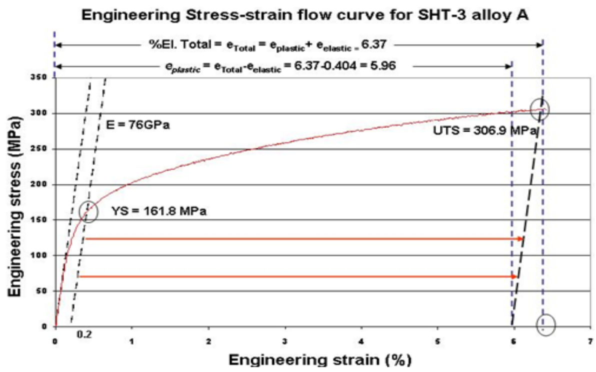


Figure 5: Engineering Stress-Strain Curve for Test 3 and Corresponding UTS, YS, %Elongation (E_{total}), $E_{plastic}$ and $E_{elastic}$ Values

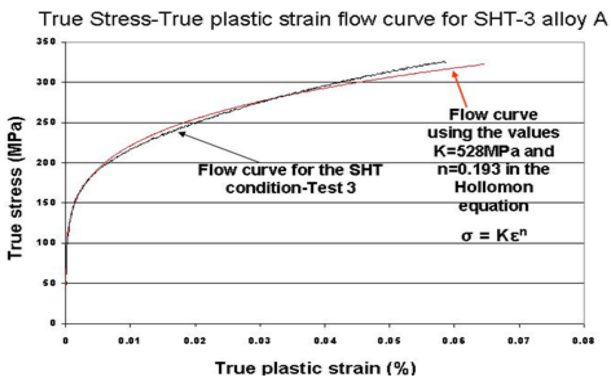


Figure 6: True Stress-True Plastic Strain Flow Curve for Solution Heat-Treated Alloy-Test 3, and the Flow Curve Derived from the Holloman Equation ($\Sigma = K\varepsilon^n$) Using K = 528 MPa and N = 0.193

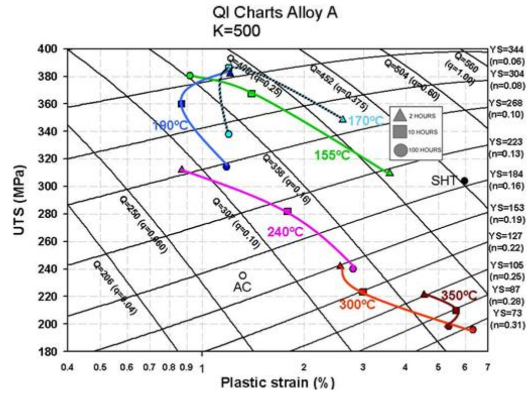


Figure 7: Quality Index Chart for Aging Conditions Corresponding to Aging Times of 2 Hrs, 10 Hrs, and 100 Hrs at Different Aging Temperatures

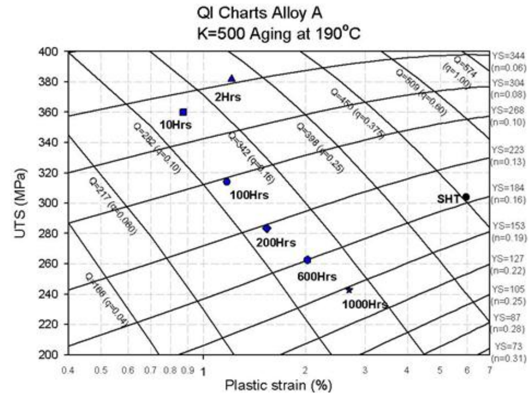


Figure 8: Quality Index Chart for Long Exposure Times at 190°c Aging Temperature